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The Effectiveness of Virtual Reality in Rehabilitation of Athletes: A Systematic Review and Meta-Analysis

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Abstract **Background:** Recent advancements in Virtual Reality (VR) and Artificial Intelligence (AI) particularly within athletic training have innovatively redefined rehabilitation strategies. This study aimed to evaluate the efficacy of VR in athlete rehabilitation was undertaken. **Methods:** This review considered inclusion of peer-reviewed studies published up to October 2023. The criteria for their inclusion were that these studies compared VR-based rehabilitation methods with traditional techniques among athletic populations. We extracted data on several factors: physical function indices, kinematic waveforms, ground reaction force (GRF), knee moments and joint angles. The study employed a random-effects (RE) model to accommodate between-study variability; subsequently, it calculated mean differences (MD) and 95% confidence intervals (CI) for meta-analytic comparison. **Results:** Incorporating findings from four studies, the review reported enhanced physical function indices in VR-based rehabilitation groups; these groups exhibited improved strength recovery—though not necessarily at an optimal speed. Researchers observed increases in ground reaction forces (GRF) and knee moments among athletes who had undergone ACL rehabilitation when they employed virtual reality (VR). The studies highlighted substantial heterogeneity–implying that the impact of VR on rehabilitation outcomes varies significantly. **Conclusion:** The marked heterogeneity among these studies suggests that various factors may influence the effectiveness of VR in rehabilitation - thus necessitating additional research for comprehensive understanding its role. Nonetheless – given its potential value as an adjunctive aid for athletic rehab – further scrutiny is indeed warranted regarding VR's applicability here.

Key Words virtual reality, rehabilitation, athletes, physical therapy, athletic training, injury recovery, joint kinematics

1. Introduction

Virtual Reality (VR) technologies have catalyzed a paradigm shift in sports medicine and athletic rehabilitation. Enhancing strength, restoring function, and preventing re-injury constitute the primary objectives of post-injury rehabilitation; thus making this phase pivotal for an athlete's career [1]. Traditional rehabilitation approaches have served as the cornerstone of therapeutic treatments for many years. Yet, immersive and interactive settings created by emerging technologies such as virtual reality (VR) offer a viable alternative that fosters recovery [2].

Virtual rehabilitation, a term denoting the application of VR in rehabilitation, employs computer-simulated settings that faithfully emulate real-world scenarios; this allows patients to engage in activities they may not safely or successfully conduct within physical environments. Such utilization enhances patient motivation and participation—thus elevating rehab process quality [3]. Furthermore it enables precise assessment and real-time feedback of performance indicators: an indispensable tool for tracking advancement.

Within the contemporary landscape of rehabilitative medicine, empirical investigations have been increasingly centered on the utilization of VR as a therapeutic modality to enhance the outcomes of exercise [5]. The burgeoning incorporation of VR into clinical practice is reflected by the escalating adoption index of this technology [6]. The synthesis of current literature reveals a substantial aggregation of data that corroborates the efficacy of VR interventions. Specifically, these studies delineate a positive trajectory of patient recovery, as evidenced by augmented functional capacities and fortified muscular strength post-ET [6]–[8].

Furthermore, the literature encapsulates investigations that extend beyond the traditional metrics of physical recovery, delving into the subjective experiences engendered by VR-based therapies [9]. These studies underscore the multifaceted advantages of this therapeutic intervention, encompassing patient satisfaction, enhancements in quality of life, perceptual shifts, adherence rates to prescribed therapy regimens, and the overall enjoyment associated with the VR exercise paradigms [10]. VR actively justifies its integration into athletic rehabilitation: it supports neuroplasticity and motor learning - key elements in the successful restoration of injured motor function. Enhanced cortical reorganization and increased neuromuscular control, integral to rehabilitating motor function post-injury, can result from enriched task-specific sensory feedback offered by VR [11]. Furthermore; customizing VR to replicate unique actions and situations within a specific sport narrows down significantly on the gap between therapeutic recovery versus competition return–a vital advantage for athletes seeking comprehensive recuperation [12].

Despite the heightened interest in using VR for rehabilitation, the evidence that supports its efficacy is still developing. Most previous studies focused on clinical populations with neurological disorders; we lack comprehensive analyses summarizing results specific to sports rehabilitation [11]–[13]. To offer a holistic view of current available evidence, amalgamate findings from distinct studies and establish VR's potential in enhancing athletic rehabilitation outcomes – systematic reviews and meta-analyses become indispensable. This systematic review thus aimed to accomplish two primary objectives: first, evaluate the influence of VR on biomechanical and kinematic parameters associated with sports performance; secondly, quantify the variability in efficacy across VR interventions within diverse athletic cohorts–ultimately assessing how effectively VR enhances functional outcomes for rehabilitating athletes.

2. Materials and Methods

A. PRISMA protocol

This systematic review was carried out and reported using the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol; the findings are displayed in Figure 1 [14].

B. PECO protocol

The PECO (Population, Exposure, Comparator, Outcomes) framework guided the formulation of our research question and the inclusion criteria for the systematic review and meta-analysis. The population of interest consisted of athletes at any level of competition who were undergoing rehabilitation for sports-related injuries. Exposure was defined as rehabilitation protocols that incorporated Virtual Reality technology. The comparator included athletes undergoing traditional rehabilitation methods without VR technology. The outcomes of interest encompassed measures of physical function, biomechanical and kinematic parameters, and sport-specific performance indices.

C. Search strategy

A comprehensive literature search was conducted across seven electronic databases: PubMed, MEDLINE, EMBASE, Cochrane Library, Web of Science, Scopus, and SPORTDiscus. The search strategy was designed to include a combination of keywords and MeSH terms related to "Virtual Reality," "Rehabilitation," "Athletes," "Sports Medicine," and "Injury Recovery." The search was limited to studies published in English, and Table 1 shows the search strings utilised.

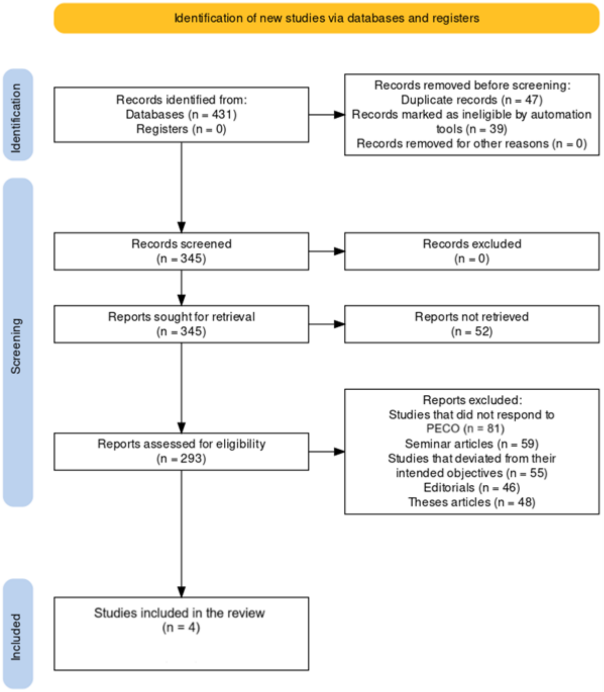


Figure 1: PRISMA utilisation for the review

D. Selection criteria

Table 2 shows the inclusion and exclusion criteria utilised for this review.

E. Data extraction protocol

Two reviewers independently screened titles and abstracts for eligibility, followed by full-text review to determine final inclusion. Discrepancies were resolved by consensus or by involving a third reviewer. The reviewers extracted data using a standardized form, which included study characteristics, participant demographics, details of the VR intervention, nature of the control intervention, outcome measures, and findings. Authors were contacted for additional data when necessary.

F. Bias assessment

The methodological quality and risk of bias of the included studies were assessed using the Risk Of Bias In Non-randomized Studies - of Interventions (ROBINS-I) tool [15] the results of which have been shown in Figure 2.

Database	Search string
PubMed	("Virtual Reality"[Title/Abstract] OR "VR"[Title/Abstract]) AND ("Athletes"[MeSH] OR "Athletic Injuries"[MeSH]) AND ("Rehabilitation"[MeSH] OR "Recovery and Rehabilitation"[MeSH])
MEDLINE	("Virtual Reality" OR "VR") AND ("Sports" OR "Athletic Performance") AND ("Rehabilitation" OR "Therapy") AND "injuries"
EMBASE	('virtual reality'/exp OR 'vr') AND ('athlete'/exp OR 'sports injury'/exp) AND ('rehabilitation'/exp)
Cochrane Library	TITLE-ABS-KEY ("virtual reality" OR "VR") AND TITLE-ABS-KEY ("athletes rehabilitation" OR "sports recovery")
Web of Science	TS=(("Virtual Reality" OR "VR") AND ("Athletes" OR "Sports Injuries") AND ("Rehabilitation" OR "Physical Therapy"))
Scopus	TITLE-ABS-KEY (("virtual reality" OR "VR") AND ("athlete*" OR "sports medicine") AND ("rehabilitation" OR "physical therapy" OR "recovery"))
SPORTDiscus	TX (("Virtual Reality" OR "VR") AND ("Athletes" OR "Athletic Injuries") AND ("Rehabilitation" OR "Therapy"))

Table 1: Search strings utilised across the assessed databases

Criteria type	Description
Inclusion criteria	
Population	Athletes undergoing rehabilitation for sports-related injuries.
Exposure	Rehabilitation protocols incorporating VR technology.
Comparator	Traditional rehabilitation methods without the use of VR technology.
Outcomes	Measurements of physical function, biomechanical and kinematic parameters, and sport-specific performance indices.
Study Design	Randomized controlled trials (RCTs), controlled clinical trials (CCTs), cohort studies, and case-control studies with comparative data between VR-based and conventional rehabilitation.
Language	Studies published in English.
Publication Date	Studies published up to October 2023.
Exclusion criteria	
Population	Non-athlete populations or athletes not undergoing rehabilitation.
Exposure	Studies not involving VR as a rehabilitation tool.
Comparator	Studies lacking a control group or a comparison between VR and traditional rehabilitation.
Outcomes	Studies not reporting specific outcomes relevant to the review.
Study Design	Case reports, conference abstracts, expert opinions, reviews, and studies without a suitable control group.
Language	Non-English language studies.

Table 2: Selection criteria for this review

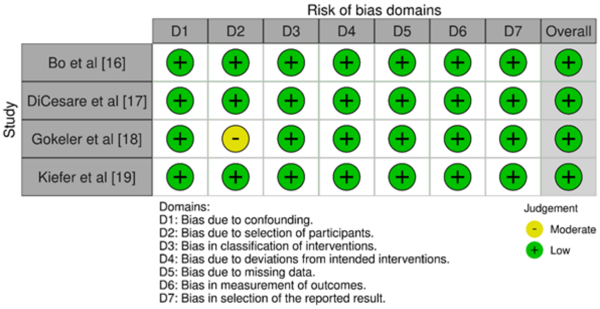


Figure 2: Bias assessment across different domains in the selected studies

G. *Meta-analysis protocol*

We conducted the meta-analysis using Review Manager (RevMan) version 5.4.1 software provided by the Cochrane Collaboration. We extracted their data for two specific outcome measures: peak knee angle and ankle dorsiflexion at peak knee flexion in terms of their mean differences (MDs) with 95% confidence intervals (CIs). We employed a random-effects (RE) model to accommodate the expected heterogeneity between studies; our assumption was that differences in athlete populations, injury types, VR intervention protocols and rehabilitation settings would cause variation among the true effect sizes within these included studies. Forest plots were generated for each outcome of interest, graphically representing the individual study findings and overall meta-analysis results. Heterogeneity among studies was evaluated using the I^2 statistic; values exceeding 50% signified substantial heterogeneity.

3. Results

A. *Study selection process*

The assessed databases initially identified a total of 431 records; however, no findings emerged from the registers. Forty-seven duplicate entries and an additional thirty-nine marked as ineligible by automation tools were eliminated before screening began - ultimately leaving only 345 eligible for scrutiny. All 345 records underwent screening; no other reasons warranted their removal. At this stage, we sought retrieval of all these records without excluding any. Nevertheless, 52 reports eluded our efforts for retrieval.

This process of eligibility assessment thus involved a total remaining count: 293 reports. The eligibility assessment excluded several reports for various reasons: 81 studies failed to meet the set PECO criteria for review response; seminar articles accounted for 59, while another 55 deviated from their intended objectives. Editorials comprised a total of 46, with thesis articles making up an additional count of 48. The comprehensive screening and assessment process deemed only four studies [16]–[19] as eligible, subsequently incorporating them into the review.

B. Assessed bias across the studies

Bo et al. [16] and DiCesare et al. [17] both received "Low" risk ratings across all domains in their studies. "Low" risk ratings primarily characterized the work of Gokeler et al. [18], with only a "Moderate" rating in the second domain; however, they still managed to garner an overall assessment of "Low" risk. Similarly, Kiefer et al. achieved: All domains also rated [19] as having "Low" risk ratings. Consequently, the overall rating for all studies was ultimately "Low" risk.

C. Demographic variables observed

Bo et al [16] conducted a study in China, dividing 12 track and field athletes with sports injuries into an experimental group and a control group. Their aim was to evaluate the effectiveness of new rehabilitation training method compared to traditional approach. The case group (mean age: 19.17 years) closely matched the control group (mean age: 19.83 years), although they did not specify the male/female ratio [16]. Similarly, DiCesare et al [17] undertook an observational study with 22 female athletes who maintained a mean age of 16 ±1.4 years; their focus remained on these young sportswomen throughout their research period. This study's aim: to evaluate jump-landing performance–using a dual approach of standard biomechanical assessment and VR-based scenario in soccer, specifically [17]. Correspondingly, Gokeler et al. [18] conducted a case-control research with 40 participants in the Netherlands; they maintained an equal male-to-female ratio 20/20 each. The mean age for the case group stood at 22.7 ± 2.3 years; conversely, the control group was marginally older with a mean age recorded as: 23.5 ± 4.3 years [18]. Kiefer et al. [19], also from the USA, conducted another observational study involving seven female athletes: they found a mean age of their participants to be 16.11 ± 1.52 years - an almost identical figure when compared with the control group's average age 16.66 ± 0.71 years [19].

D. Rehabilitation-based inferences observed

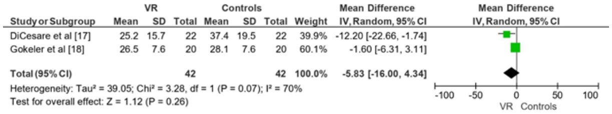
In their study, Bo et al [16] compared two groups of track and field athletes who underwent rehabilitation for sports injuries. The experimental group (Group A) employed a novel rehabilitation training method - one that incorporated AI and VR technologies; whereas Group B utilized traditional approaches to rehabilitation. The results revealed significantly higher physical function indices in Group A: its values surpassed 96%, while those of Group B fell below at only 87%. This suggests that the innovative approach not only outperformed traditional methods but also played a pivotal role in enhancing strength recovery. Group A, however, did not achieve optimal recovery speed; this was attributed to the brief six-week duration of their rehabilitation period [16]. DiCesare et al. [17], using both standard biomechanical and VR-based assessments, analyzed soccer players' performance. They found that VR distinctly influenced the kinematic waveforms of lower-extremity joint movements during a jump-landing task's landing phase. When we applied VR conditions instead of the standard assessment conditions [17], differences in hip and ankle angles became evident among the athletes.

In their study, Gokeler et al. [18] incorporated a total of 40 participants: 20 athletes who had undergone ACLR—Anterior Cruciate Ligament Reconstruction—and an equal number without any surgical intervention serving as controls. The researchers leveraged VR technology to evaluate rehabilitation outcomes; they noted that when engaging with VR, the ACLR group displayed increased values for GRF/BW—Ground Reaction Force over Body Weight ratio and knee moment normalized to body weight. Furthermore, there appeared to be a slight rise in knee angle at vGRF within this same group during use of the VR system [18]. In their investigation of the effects of aNMT on soccer athletes, Kiefer et al. [19] studied five trained competitors and contrasted them with two untrained controls; they observed a significant reduction in internal hip rotation during the loading and push-off phases after these subjects underwent training with aNMT: moreover at the 50% stance phase post-training — there was an appreciable 19% decrease in knee abduction. Despite this notable alteration, statistical significance remained elusive [19].

E. Peak knee angle and flexion observed

Incorporating two studies [17], [18], Figure 3 presents a comparison of peak knee angles between VR and standard assessments: the combined total Mean Difference (MD) across both studies is -5.83 degrees, with a confidence interval at 95% CI [-16.00 to 4.34]. The pooled effect size implies that knee angles, on average, appear smaller in standard assessments compared to VR; nevertheless, this overall effect does not achieve statistical significance. We quantify the heterogeneity with $Tau^2 = 39.05$–a Chi^2 value of 3.28 (df = 1, P = 0.07) and an I^2 statistic registering at a modest 70%. The overall effect test yields a Z-score of 1.12 and a P-value of 0.26; it suggests that across the studies there exists no significant difference in peak knee angles between VR and standard assessment methods.

In Figure 4, we observe a comparison between VR and standard assessments of ankle dorsiflexion at peak knee flexion; this meta-analysis includes results from two studies [17], [18]. The combined MD for both these studies is -7.00 degrees, with the 95% CI extending from -18.46 to 4.47: an important insight into the range of potential error or variability in our findings. This pooled MD implies: ankle

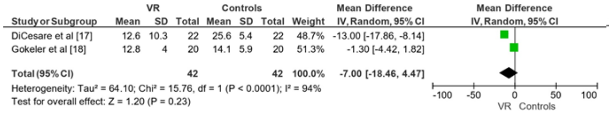


Study or Subgroup	VR Mean	VR SD	VR Total	Controls Mean	Controls SD	Controls Total	Weight	Mean Difference IV, Random, 95% CI
DiCesare et al [17]	25.2	15.7	22	37.4	19.5	22	39.9%	-12.20 [-22.66, -1.74]
Gokeler et al [18]	26.5	7.6	20	28.1	7.6	20	60.1%	-1.60 [-6.31, 3.11]
Total (95% CI)			**42**			**42**	**100.0%**	**-5.83 [-16.00, 4.34]**

Heterogeneity: Tau^2 = 39.05; Chi^2 = 3.28, df = 1 (P = 0.07); I^2 = 70%

Test for overall effect: Z = 1.12 (P = 0.26)

Figure 3: Comparison of peak knee angle using VR and standard assessments



Study or Subgroup	VR Mean	VR SD	VR Total	Controls Mean	Controls SD	Controls Total	Weight	Mean Difference IV, Random, 95% CI
DiCesare et al [17]	12.6	10.3	22	25.6	5.4	22	48.7%	-13.00 [-17.86, -8.14]
Gokeler et al [18]	12.8	4	20	14.1	5.9	20	51.3%	-1.30 [-4.42, 1.82]
Total (95% CI)			**42**			**42**	**100.0%**	**-7.00 [-18.46, 4.47]**

Heterogeneity: Tau^2 = 64.10; Chi^2 = 15.76, df = 1 (P < 0.0001); I^2 = 94%

Test for overall effect: Z = 1.20 (P = 0.23)

Figure 4: Comparison of ankle dorsiflexion at peak knee flexion using VR and standard assessments

dorsiflexion may indeed be greater on average during VR assessment; however, the statistical insignificance of this effect remains when we consider data from both studies. The heterogeneity in effect sizes presents a substantial issue – exemplified by a Tau^2 value of 64.10 and a Chi^2 statistic reading at 15.76 (df =1) which held high significance with P <0.0001 indicating considerable diversity among these measurements. Moreover, our I^2 statistic a robust measure for determining consistency or inconsistency stands starkly at 94%, underlining an overwhelming degree of discordance among study outcomes–a noteworthy point to address in future research efforts. Comparing VR assessments to standard assessments, the overall effect test yields a non-significant difference in ankle dorsiflexion; it presents with a Z-score of 1.20 and an associated P-value 0.23: these results do not denote statistical significance.

4. Discussion

Our study reveals AI and VR's multifaceted importance in sports rehabilitation, emphasizing their emerging role for the evaluation of athlete performance. Applying these technologies within sports medicine promises to revolutionize injury recovery methods for athletes while also measuring - and subsequently improving- athletic performance: a vital element in every competitive field. The results have significant future implications; advancements and increased accessibility of AI and VR technologies might evolve their integration into standard practice within sport medicine. This potential development could yield dual benefits: it could not only expedite the recovery process for athletes, but also enhance performance through intricate biomechanical analysis. Moreover, immersive simulation-based training would enrich this further–thus offering a distinct competitive edge.

We must acknowledge a few factors: first, the unique population we targeted athletes; secondly, this area's relatively underdeveloped research status. These elements contribute directly to the limited number of studies we uncovered in our review. The field still emerges particular focus on athletic populations has resulted in less extensive investigation compared with broader applications like AI and VR. This underscores a significant opportunity for future inquiries to consider an expansion of evidence base through exploration into sports-specific contexts may be key unlocking these technologies' complete potentiality. As a deluge of forthcoming research looms, we not only anticipate an extensive understanding but also widespread adoption of these cutting-edge instruments. This anticipation will pave the way for innovative treatments strategies and training methods that cater precisely to athletes' needs.

Gazendam et al. [20] and Lal et al. [21] offer insights into the application of VR in rehabilitation, focusing on orthopedic surgery and general tele-rehabilitation in India respectively; their findings provide a comprehensive understanding at graduate level: Both reviews: they propose that VR-based rehabilitation presents a promising field; one capable of enhancing patient outcomes–potentially slashing costs in the process.

In their systematic review and meta-analysis specifically examining the use of VR in total knee arthroplasty (TKA) rehabilitation, Gazendam et al. [20] found no significant short-term differences in pain scores between VR-based and traditional rehabilitation. They acknowledged an improvement in functional outcomes at 12 weeks and 6 months post-operation for those who had undergone VR-based rehabilitation; however, they recognized the evidence's certainty as moderate to low. Furthermore, a potential cost-savings emerged in one trial that they identified. Our conducted study might have more broadly explored the impact of VR on rehabilitation across various types of orthopedic and sports-related injuries not just limiting it to TKA. Should our study's findings align with Gazendam et al. [20], it would imply a consistent pattern: VR proves advantageous for functional outcomes over an extended rehabilitation period. Conversely – should our results demonstrate immediate improvements in pain or function – this would stand in contrast; they found no short-term benefits regarding pain relief.

On the other hand, Lal et al. [21] conducted a systematic search on tele-rehabilitation and virtual physical therapy, with particular focus within the Indian context; they found that incorporating tele-rehabilitation and virtual reality into India's telehealth delivery system is cost-effective–an approach especially beneficial for remote athlete populations. The review they conducted affirms tele-rehabilitation's effectiveness and endorses the use of diverse technologies–such as smartwatches and movement sensors; in furnishing remote care. A parallel to Lal et al. 's [21] findings on our part could imply a worldwide pattern: an increasing recognition for VR and tele-rehabilitation not only boosting access to healthcare, but also augmenting patient outcomes—irrespective of geographic location. Should our study discover scant evidence of the effectiveness or cost benefits of VR in rehabilitation, it would signify a divergence. This disparity could potentially result from dissimilarities in healthcare infrastructure, patient populations, or reviewed regions' and studies' rehabilitation protocols.

Comparing our study's findings to those reported by Putranto et al. [22], we both recognize the escalating use of VR in sports; however, our focuses differ. In Section 22, the focus lies on exploring the extensive applications of VR in sports education and training; particularly underlining how HMDs coupled with motion capture systems prevail. Their research not only indicates VR's popularity but also its burgeoning importance as a tool for enhancing decision-making and prediction within athletic training. Conversely, our study delved into distinct uses of VR: rehabilitating sports injuries and evaluating athletic performance – thus shedding light on the efficacy of incorporating VR into these specific rehabilitation routines at an advanced level.

Asadzadeh et al. [23] investigate the effectiveness of VR, focusing specifically on VR-based exercise therapy for diverse conditions; their findings align with ours - they note positive impacts on pain management, functional ability and muscular strength. Similar to our study's results indicating an enhancement in physical function indices and biomechanical parameters during rehabilitation they identify a potential role for VR in improving these aspects across various conditions. Asadzadeh et al. [23] underscore the utilization of consumer VR devices such as Nintendo Wii and Kinect, proposing a more expansive and accessible application of VR in exercise therapy; contrastingly, our study focuses its use on high-performance athletes - thus rendering it more specialized – with relevance to clinical rehabilitation settings. In their investigation, Bilika et al. [24] present a scoping review; this suggests that VR-based exercise therapy not only reduces pain but also improves functional outcomes. Our study echoes these findings: it reveals superior recovery results among athletic cohorts through VR-assisted rehabilitation. Bilika et al. [24] also acknowledge the limitations of their findings due to heterogeneity and methodological disparities across studies–a caution that holds relevance for our study as well; we confront variability in results, thus necessitating further research.

Pragmatic impediments frequently hinder investigative pursuits to decode the biomechanical foundations of risks for sport-induced injuries [25]. These obstacles range from environmental factors to operational challenges, including difficulties such as limited equipment availability and unpredictable weather conditions, along with a need for adherence from sports organizations and an inadequacy in standardized experimental settings [26]. In response to these limitations, researchers have chosen a path that involves reconstructing sport-specific maneuvers inside laboratory environments. The domain involves analyzing anticipatory responses in handball, sprinting acceleration dynamics [27], football kicking biomechanics, volleyball blocking strategies, and the complex interaction of basketball skills such as passing, dribbling and shooting [28].

These skills replicate in a controlled, ersatz sporting context; however, when we extrapolate this data to the actual field of play–we encounter limitations in ecological validity. Moreover: research that delves into nuanced biomechanics associated with injury susceptibility is sparse and specifically focuses on those delineated via traditional biomechanical analysis modalities – such as quantification of external knee abduction moments [29] – remains scanty.

VR technology's advent offers a cutting-edge solution to the fundamental limitations of traditional biomechanical evaluations: it creates immersive, sport-specific situational analyses. Through this method–Virtual Reality–authentic athletic exertions and competitive engagements can be replicated within a controlled experimental setup [30], [31]. This groundbreaking strategy potentially produces a more realistic depiction of injury risk profiles and the biomechanical adaptations that result from athletic training. By scrutinizing the mechanics of athletes as they perform basic sporting tasks in a simulated, complex facsimile of the competitive environment, it achieves this [32]. The dynamic elements within this copycat world include player-to-player interactions, manipulation of objects and utilitarian use for sports equipment. VR applications in biomechanical research have seeped into handball throw kinematics; tactical decision-making processes in rugby; and inherent biomechanical patterns associated with soccer cutting maneuvers yet mostly focusing on their relevance to injury-specific movement patterns [33]. Biomechanical research pervades handball throw kinematics through applications of VR: by examining athletes' mechanics within a complex simulation mimicking competitive environments a setting that incorporates not only fundamental tasks but also dynamics like player interactions, object manipulation and use-of-equipment utility seen in real-life games [34]. This scrutiny extends further; it probes deeply into tactical decision-making for rugby too - demonstrating how immersive technology is revolutionizing sport analysis at graduate level studies where precision matters most. However primordially it focuses on soccer cutting maneuvers: investigating their inherent biomechanical patterns yet primarily emphasizing relevance towards different types of injuries [34].

A. Recommendations for sports-related applications

The findings of this review shape our recommendations for future research and clinical practice: we advocate that rehabilitation programs while contemplating the integration of emerging technologies like AI and VR scrutinize their specific attributes; they should deliberate over the potential benefits these advancements may present. Significantly, observed improvements in physical function indices with AI & VR usage suggest a substantial enhancement to sports-related injury rehabilitation processes could be within reach through these innovations. Even when they employ advanced technology, rehabilitation professionals must remain cognizant of the optimal recovery duration; superior results may not be yielded by a brief period in rehabilitation.

As we observe the impact of VR on kinematic waveforms for lower-extremity joint movements particularly during dynamic tasks like jump-landings; a deeper exploration into its potential emerges as necessary. VR might provide a more nuanced and detailed assessment of movement patterns: aspects that standard biomechanical evaluations could potentially overlook. This investigation, in turn, may pave way not just towards individualized rehabilitation interventions but also towards targeted ones at an unprecedented level of enhancement. Assessing the impact of VR utilization in rehabilitation specifically for populations with specific injuries like ACLR on biomechanical outcomes: ground reaction forces and knee moments, is a necessary task. The advantage lies potentially within its influence on compliance and motivation; by offering an engaging we might even venture to say varied rehabilitation process, VR could prove instrumental.

Furthermore, a deeper investigation into the application of aNMT in rehabilitation and its impact on hip and knee mechanics is imperative. A study uncovered substantial decreases in internal hip rotation; furthermore, it hinted at potential benefits from aNMT by also revealing a non-significant reduction in knee abduction - yet emphasized the urgent necessity to confirm these findings' statistical significance as well as their clinical relevance through larger sample sizes. Striving to standardize VR assessment protocols in future studies and ensuring their consistent application across diverse patient populations and injury types could mitigate methodological heterogeneity. Amplifying result generalizability may become possible by considering larger sample sizes with balanced gender distributions. The meta-analysis unveiled a significant level of heterogeneity, implying a potentially varying impact of VR on rehabilitation outcomes; thus, interpreting this data warrants an approach characterized by prudence.

5. Limitations

Certain limitations of this study deserve careful consideration when interpreting the findings: these constraints are intrinsic to the study design; they hinge on sample characteristics, and most significantly–they relate to methodological approaches utilized within selected studies. Firstly, the smallest study in these studies involved only seven participants [19], resulting potentially in a type II error due to its relatively small sample size. Additionally, small sample sizes limit this study's power to detect an actual effect if present and decrease the findings' generalizability. Moreover, if the included studies are not representative of a larger body of research for outcome measures such as peak knee angle and ankle dorsiflexion at peak knee flexion; then their limited number could introduce bias into our meta-analysis. Secondly, across studies, the participants' demographic characteristics presented variation; this introduces heterogeneity potentially confounding results. For example: one study [16] did not specify its gender distribution and–furthermore–the age ranges differed among all these studies. The influence of such demographic variations on rehabilitation outcomes cannot be understated; age and gender may profoundly affect responses to VR rehabilitation. Thirdly, the meta-analysis unveiled significant statistical heterogeneity; high I² values were evident for both peak knee angle and ankle dorsiflexion at peak knee flexion outcomes–a clear suggestion of inconsistent results among the studies. This hints towards potential underlying differences in study populations, interventions or unaccounted measured outcomes within this comprehensive analysis.

6. Conclusion

After synthesizing data from the included studies; our results revealed that compared with traditional rehabilitation methods VR did not yield statistically significant enhancements for these biomechanical parameters under assessment. Both the peak knee angle and ankle dorsiflexion showed no statistical significance in their mean differences; this implies that VR did not provide a clear advantage over standard assessment for these specific measures – thus suggesting an equal footing between them. The analysis also faced substantial heterogeneity across studies: a variation in results between diverse research settings and participant groups. We can attribute this heterogeneity to three factors - varying study designs, participant demographics, and the nature of VR interventions used in these studies. However; small sample sizes combined with a limited number of included studies imposed additional constraints on both robustness and generalizability of our drawn conclusions. Based on our synthesis of evidence, however, we cannot conclusively indicate that VR technology more effectively improves peak knee angle and ankle dorsiflexion than standard rehabilitation practices.

Conflict of interest

Authors declares no conflict of interests. Author read and approved final version of the paper.

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